BBC

RESEARCH DEPARTMENT

REPORT

AMPLITUDE MODULATION RADIO BROADCASTING:
Application of companding techniques to the radiated signal

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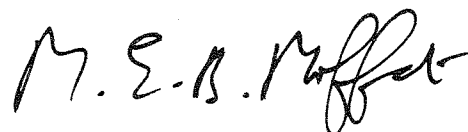
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Summary

Double-sideband amplitude modulation techniques have been applied in radio broadcasting since its earliest days, and, in spite of the introduction of other systems in the intervening years and of further technological developments in the coming years, seem likely to be used for a very important part of the service provided by the BBC well into the future.

Throughout the years there has been a continuing interest in achieving efficient transmitter operation without significantly sacrificing the service provided. This Report describes a power-saving technique which may be applied to double-sideband amplitude modulation transmitters. The technique operates by imposing dynamic compression on the radiated signal, and relies on the action of receiver automatic-gain-control circuits to compensate for this compression at the receiver.

Measurements and listening tests suggest that use of the proposed technique could, in some circumstances, result in considerable power saving with minimal effect on the quality of reproduced programmes. It is, however, recommended that an extended field trial should be conducted, using a representative high-power transmitter, to prove the system fully before an extensive introduction in service is put into effect.

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1. Introduction

Double-sideband amplitude modulation has played a major role in radio broadcasting engineering since the earliest days. It has continued in use for domestic broadcasting in the United Kingdom since the first '2 LO' transmissions by the BBC (then the British Broadcasting Company) in 1922, and for External Broadcasting since 1932. Since 1955, the very-high-frequency frequency modulation (v.h.f., f.m.) network has increasingly provided high-quality domestic services, but the medium frequency, amplitude modulation, double-sideband (m.f., a.m. d.s.b.) transmitter network nevertheless continues to make an essential contribution to the overall national coverage provided by the BBC.

Throughout the years there has been an interest in improving a.m. transmitter efficiency, while maintaining the standards of quality of the reproduced programme, in order to economise on transmitter running costs, and various means have been applied to this end. This Report is concerned with power saving techniques which operate by regulating the output of the transmitter dynamically according to the level of the applied modulating signal. It deals particularly with a system in which the amplitude of the radiated signal is compressed as the level of modulation is increased − carrier and sidebands being controlled so that the correct modulation index is always maintained.

With this technique, the automatic-gain-control (a.g.c.) systems incorporated in virtually all receivers tend to compensate for the compression introduced at the transmitter, and thereby to restore the relative levels of the reproduced sound signal to those of the signal applied at the transmitter input.

This report explains the proposed companding technique and describes laboratory and over-air tests carried out to establish its viability.

2. Conventional double-sideband amplitude modulation transmission

Fig. 1 shows modulation envelope waveforms illustrative of conventional double-sideband amplitude modulation transmission. Fig. 1(a) indicates the unmodulated carrier and Figs. 1(b), (c) and (d) the envelopes for sinusoidal modulating signals at modulation indices (m) of approximately 0.1, 0.5 and 1.0 respectively. The radiated power for sinusoidal modulation increases with modulation index according to the law $1 + \dfrac{m^2}{2}$, and at full modulation reaches 1½ times the power of the unmodulated carrier.

The radiated signal is demodulated at the receiver to reproduce the sound programme. Virtually all receivers incorporate an automatic-gain-control (a.g.c.) system which generally responds to the mean level of the radio frequency

(a)   *(b)*   *(c)*   *(d)*
unmodulated   10% modulation   50% modulation   100% modulation
carrier
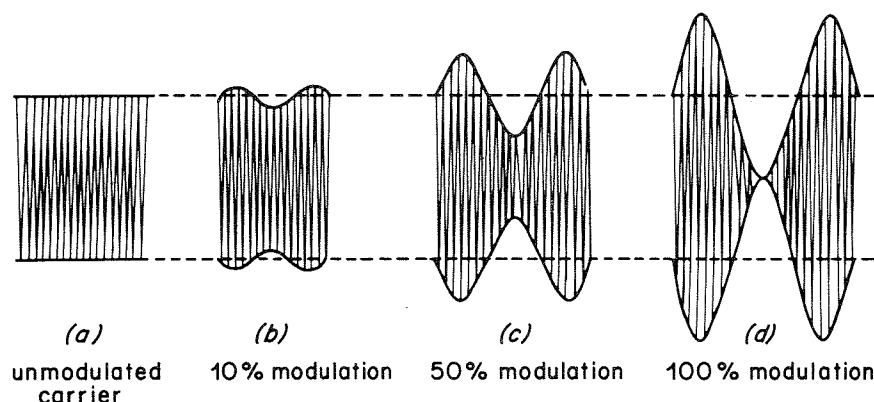
Fig. 1 − Modulation envelope, conventional double-sideband amplitude modulation.

(r.f.) signal (i.e. to the carrier level)*. The a.g.c. is arranged, within its range of control, to keep the level of the modulated signal substantially constant at the demodulator, irrespective of the level of the signal at the aerial. A.G.C. action thus tends to equate the reproduced levels of programmes radiated from transmitters providing different signal strengths at the receiver, and further, to compensate for the effects of fading** on the propagation path between transmitter and receiver.

3. Dynamic output control

From the 1930's techniques have been described for improving transmitter efficiency by adjusting the transmitter output dynamically according to some law related to the level of the modulating signal.[1,2,3]

In recent years interest has been revived in two such techniques having a degree of similarity but differing, nevertheless, in their basic principle of operation. In one case the carrier level for low modulating conditions is set below its full modulation value, and is increased dynamically to accommodate high levels of modulating signal; in the other, a conventional, or possibly even enhanced, quiescent carrier level is adopted and the complete modulated output, carrier and side bands, is reduced in amplitude (i.e. compressed) at high modulation levels.

In the former case, if the equipment is arranged to give conventional modulation indices towards the top of the modulation range, the modulation index will be disproportionately large for lower modulation levels. The dynamic range of the audio signal reproduced by a receiver incorporating a.g.c. will consequently differ from that applied to the transmitter; it will, in effect, be compressed. Further, the reproduced level of any interference will tend to be raised by the action of the a.g.c. during quiet programme passages.

In the second case, though the radiated output from the transmitter is compressed at high levels of modulation, the modulation index is kept the same as that of a conventional system throughout the modulation range. The action of the receiver a.g.c., in maintaining a constant signal level at the detector, therefore acts also to

maintain at the audio output of the receiver the same relative levels of the programme-signal components as were applied at the transmitter input.

This Report is concerned with an investigation into the second form of dynamic control.

4. Dynamic compression of radiated output at high levels of modulation

4.1. General

In the dynamic radiation-compression system now being considered, the transmitter output signal is compressed syllabically according to some chosen law as the level of modulation is increased. This action is specifically arranged to ensure that the modulation index is the same as for a conventional system throughout the full modulation range. The effect is indicated in Fig. 2, which shows the output envelope waveform of a radiation-compressed system, using, for illustration, a particular control characteristic which maintains a constant maximum peak output voltage. Fig. 2(a) indicates the unmodulated carrier and Figs. 2(b), (c) and (d) indicate output waveform envelopes for sinusoidal modulation at modulation indices of about 0.1, 0.5, and 1.0 respectively.

Comparison with Fig. 1 shows that conventional modulation indices have been maintained despite the compressor action.

The natural control action of a conventional receiver a.g.c. system tends to offset the variations of transmitter output power, now being introduced deliberately, and thus ensures that the audio programme is reproduced throughout with appropriate relative levels.

The overall arrangement, comprising compression at the transmitter and compensatory expansion by the receiver a.g.c. circuits, in fact constitutes a pilot tone compander, with the radiated carrier forming the pilot tone.

4.2. Potential advantages of radiation compression

The principal object of dynamic a.m. radiation compression is reduction of transmitter input mains power, and hence of running costs, without significantly degrading the quality of reproduced programme. Reduction of input power is related, through the transmitter efficiency

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*An alternative but less common receiver a.g.c. system responds to the peak level of the modulated signal. With a conventionally modulated signal, a receiver of this type compresses the demodulated signal at higher modulation levels.

**Excluding the effects of selective fading.

Fig. 2 — Modulation envelope, radiation compressed double-sideband amplitude modulation with constant maximum peak output level.

(a)	(b)	(c)	(d)
unmodulated	10% modulation	50% modulation	100% modulation
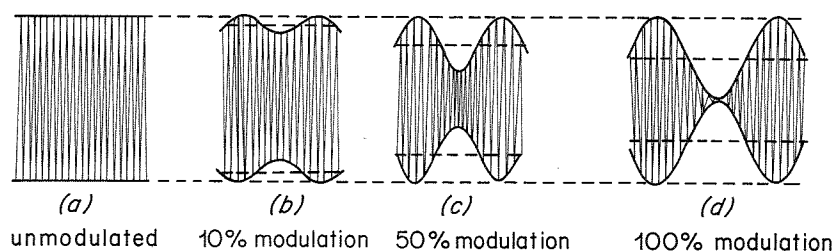
law, to the reduction of mean output power which can be achieved; this is discussed quantitatively in a later Section.

Further efficiency improvement may be possible in some circumstances by re-optimising the transmitter operating conditions to take advantage of the reduced maximum peak voltage or maximum peak power output associated with the particular compression law being used. Such reduction of peak requirement offers potential for cost saving also through the possibility of using components of reduced peak voltage rating in the high-power stages of the transmitters.

Certain specific compression laws may have their own particular advantages. For example, a substantially constant *power* arrangement can be envisaged which would tend to reduce surges in power demand; such an arrangement might be of interest, for example, where several high-power transmitters on one site are radiating one programme simultaneously.

So far only the potential power-saving and cost-reducing aspects of radiation compression have been mentioned — it has tacitly been assumed that the quiescent carrier will be of conventional level. However, there is the alternative option of setting an enhanced level of quiescent carrier, thus actually increasing the transmitter power output under low modulation conditions, and reverting to, say, normal conditions at high modulation. By this means the service provided by the transmitter could be increased without requiring a corresponding increase of peak output rating.

Adoption of this alternative arrangement is unlikely to be widely practicable to a significant degree in existing m.f. transmitters because of regulatory restraints on the unmodulated carrier power and because of practical considerations of transmitter operation. However, the technique could have application in short-wave broadcasting, and in the development of economical new transmitters.

4.3. Potential sources of programme quality impairment

It was noted earlier (Section 4.1) that the transmitter/ receiver combination, operating as described in this Report, in fact constitutes a compandor. Attention must therefore be given to the possible introduction of impairments caused by the companding action, so that any quality degradation can be assessed and kept in mind when considering the overall merits of compressed radiation operation.

First, there is risk of subjective impairment due to a disturbance of the balance of relative programme levels. This can occur in steady state if the accuracy of expander tracking is not adequate, or momentarily if tracking is not sufficiently rapid to avoid audible disturbance of the reproduced programme while the programme level is changing.

In an a.m. companding system the expander characteristic is determined by the a.g.c. in listeners' receivers so is not under the control of the broadcaster. However, as is discussed later, measurements on a number of a.m. receivers and laboratory listening tests suggest that quality impairment due to level perturbation is unlikely to be a common problem particularly over the relatively small compression/expansion range being considered.

A second potential source of impairment in a companding system results from the possible effects of noise and interference. In an a.m. companding system in which the carrier level returns to its conventional value in quiescent conditions, the background noise will be normal when modulation is low. However, as the level of modulation is increased and the radiated signal is compressed, the action of the receiver a.g.c. to maintain normal overall gain will raise the reproduced level of any noise or interference present on the link between compressor and expander, i.e. programme modulation of such noise and interference will occur and may become audible.

In all companding systems the higher level audio signals which cause such compandor action themselves tend to mask the increased levels of noise and interference which results. Impairment due to programme-modulated interference will of course only occur when interference is present — i.e. under adverse reception conditions — and its effects will not be great when, as will be proposed in this Report, the amount of compression/expansion introduced is relatively small.

4.4. The transmitter as compressor

4.4.1. Static considerations

The output compression characteristic required to produce a constant peak output voltage characteristic (Fig. 2) can readily be achieved in a low-power implementation by a circuit arrangement such as that indicated in Fig. 3.
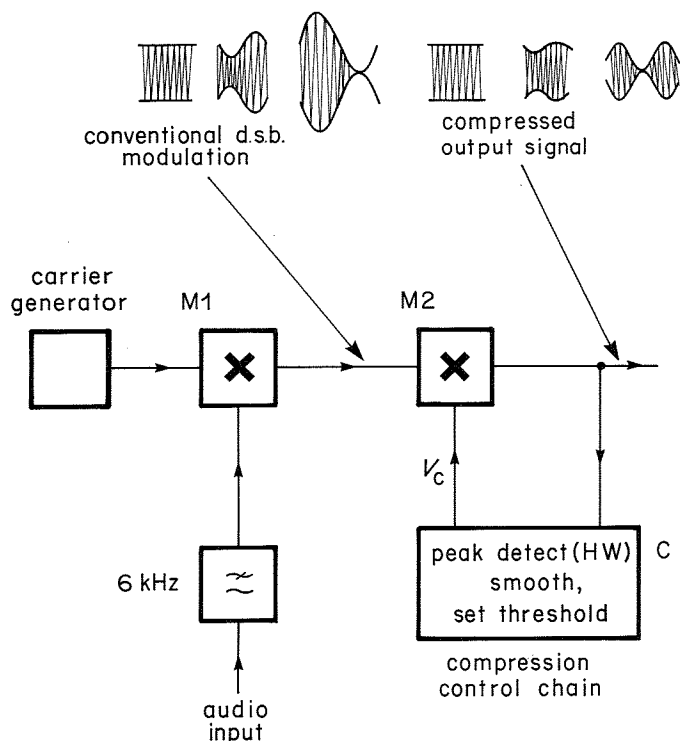

conventional d.s.b. modulation

compressed output signal

carrier generator   M1   M2

6 kHz   ≈

audio input

peak detect(HW) smooth, set threshold   C

V_c

compression control chain

Fig. 3 — Radiation-compression apparatus, output-controlled.

The arrangement comprises essentially two modulators in cascade; the first, M_1, operates conventionally and feeds a normal amplitude-modulated signal to one input of the second modulator, M_2. The output of modulator M_2, in addition to providing the signal to be radiated, feeds a control chain, C, in which the signal is rectified, peak-detected, referred to a 'threshold' level reference and passed through attack/recovery-rate control circuits back to its second input.

Radiation compression as illustrated in Fig. 3, is output-controlled, with the control signal, Vc, derived directly from the radiated signal. Compression can equally well be input-controlled, with Vc derived from the audio input signal and a DC component added, as appropriate, to set the level of the quiescent carrier. Such an arrangement is illustrated in block schematic form in Fig. 4, which indicates the provision of controls for the carrier level, the amount of compression and the compression threshold (i.e. the modulation index value at which compression begins). The range of compression laws available may, of course, be extended indefinitely by introducing non-linear elements in the control-voltage derivation circuits.

The use of input control considerably increases the flexibility of the system and enables the law of control to be changed more simply.

4.4.2. Dynamic considerations

The circuits of Figs. 3 & 4, and indeed their modes of operation, are essentially similar to that of a simple, syllabic, sound-signal limiter, and the dynamic characteristics established for such limiters[4] give an indication of the requirements for the r.f. radiation-compression circuits now being considered.

In practice an attack time of about 0.3ms and a recovery time option of some 125 ms to 250 ms were provided in the experimental equipment first constructed. Use of a shorter attack time increases the risk of quality impairment due to over-rapid control[4], while an increase would either lengthen the period of signal overshoot in a simple control arrangement, or demand an increase in the audio signal delay time in the non-overshoot, input-controlled, arrangement discussed below.

Selection of recovery time did not appear to be critical, but, in informal laboratory tests using a number of conventional receivers with the radiation compression arrangement indicated in Fig. 3 some preference was indicated for a recovery time of about 200 ms.

Where the transmitter can accept 100% modulation, operating conventionally, the transition in the compression mode from a low level of modulation to a high level of modulation — in the limit from no modulation to full modulation, i.e. from the state represented by Fig. 2(a) to that
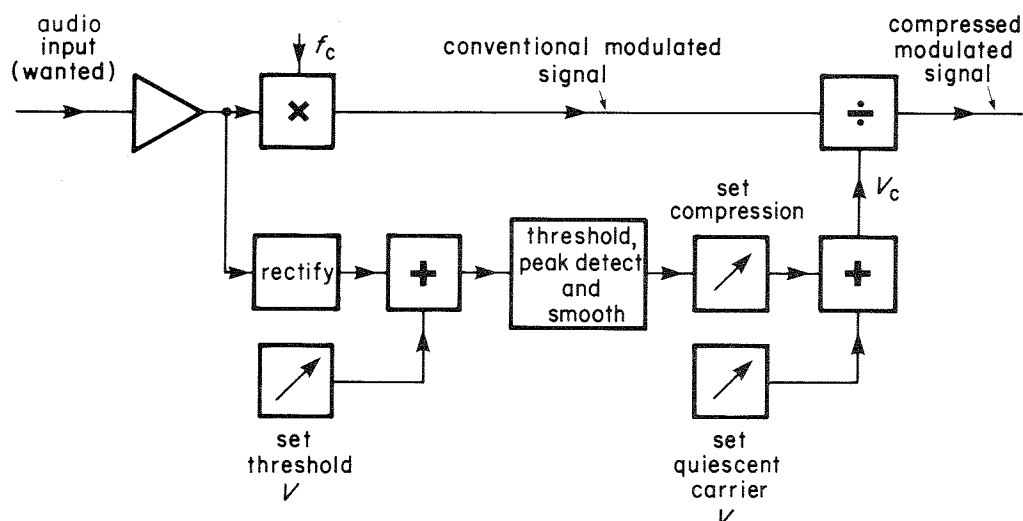
audio input (wanted)

f_c

conventional modulated signal

compressed modulated signal

threshold, peak detect and smooth

rectify

set threshold V

set compression

V_c

set quiescent carrier V

Fig. 4 —
Radiation-compression
apparatus, input-
controlled.

of Fig. 2(d) — can be made via the condition illustrated in Fig. 1(d). Thus the peak level of the radiated signal is allowed momentarily to exceed its ultimate value but it is thereafter rapidly reduced to that level as compression is imposed.

If, however, some advantage in terms of component rating is being taken in reducing the required output voltage swing, even this momentary peak of output signal amplitude cannot be allowed. However, the necessary characteristics can readily be achieved by means of the non-overshoot delay-line limiter techniques described elsewhere[4]. Here an audio-signal delay circuit is included in the audio input to the variable-gain path, but not in the feed to the circuits in which the control signal is derived. By this means the gain in the variable-gain element can be reduced appropriately in anticipation of the arrival of a high-level audio signal, and signal overshoot at the system output can thereby be eliminated.

4.4.3. High-power applications

The arrangements indicated in Figs. 3 and 4 have been implemented at low power for laboratory experiments. However, the required operating characteristics can also be achieved for high-power applications by use of appropriate circuit arrangements.

Figs. 5, 6 and 7 suggest means of achieving radiation compression on various types of high-power transmitter. In each case the necessary control voltage can be derived by the techniques discussed earlier.

4.5. The receiver as expander

4.5.1. Static a.g.c. performance

Receiver a.g.c. circuits are intended to equate the audio outputs demodulated from received r.f. signals over a large range of levels. The deliberate compression of the radiated signal now being considered amounts to only a few decibels, so should be trivial compared with the normal range of receiver a.g.c. control. Static tracking should therefore be entirely adequate for the present purpose under normal reception conditions.

4.5.2. Dynamic a.g.c. performance

Though the range of static a.g.c. control provided should normally be appropriate for the present purpose there is the further requirement that dynamic tracking should be sufficiently rapid. When, for example, the transmitted signal is rapidly compressed the demodulated receiver output will momentarily be lower than it should have been — recovering to the correct level only as the a.g.c. responds to the change of signal strength. Conversely, as the radiated signal recovers from compression (i.e. as the depth of modulation falls) the demodulated output will tend to be high until the a.g.c. circuit has reached equilibrium. The a.g.c. characteristics of some 14 receivers of different manufacture were examined within their effective a.g.c. ranges, using as a test signal an r.f. carrier with about 50% modulation — the whole being switched repeatedly between two levels 6 dB apart. (This figure probably represents the maximum amount of radiation compression likely to be considered in practice). The action of the receiver a.g.c. was then assessed in terms of the gain fluctuation characteristics of the demodulated output.
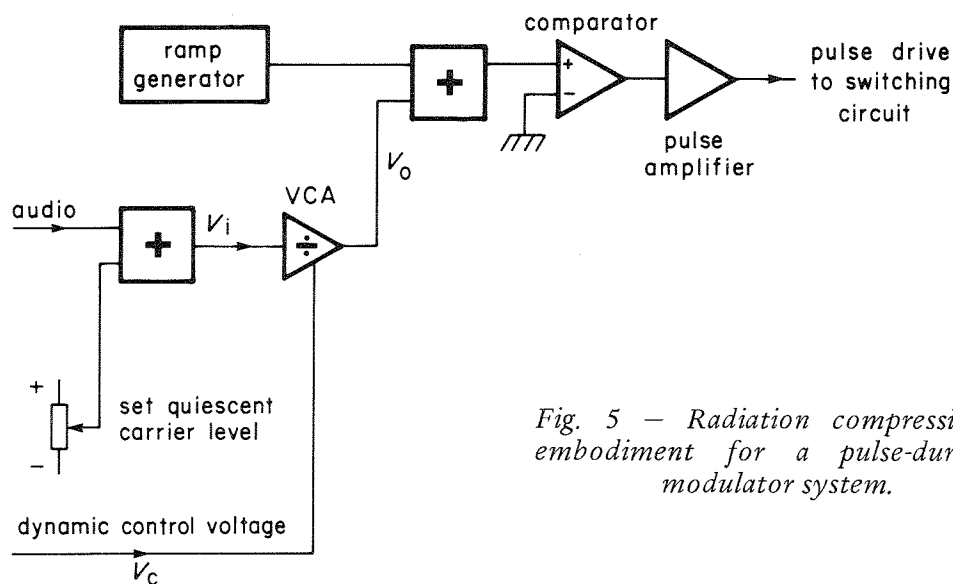
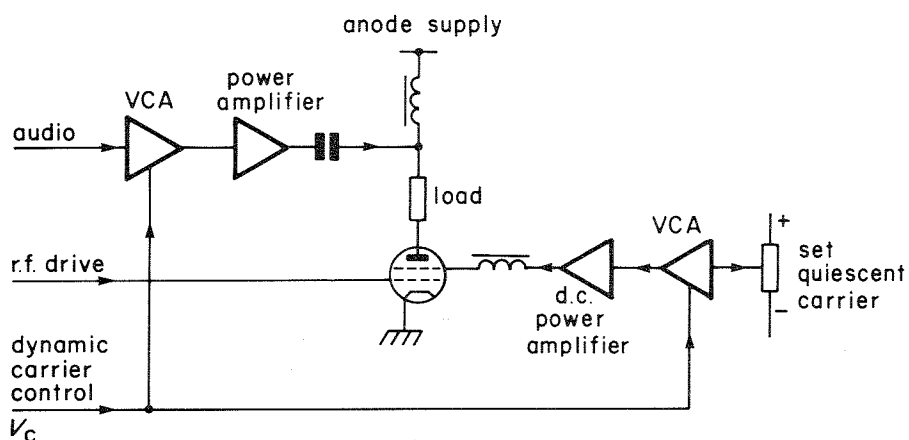Fig. 5 — Radiation compression : embodiment for a pulse-duration modulator system.

Fig. 6 — Radiation compression : embodiment for anode-modulated tetrode where the quiescent carrier level is independent of conventional modulator.
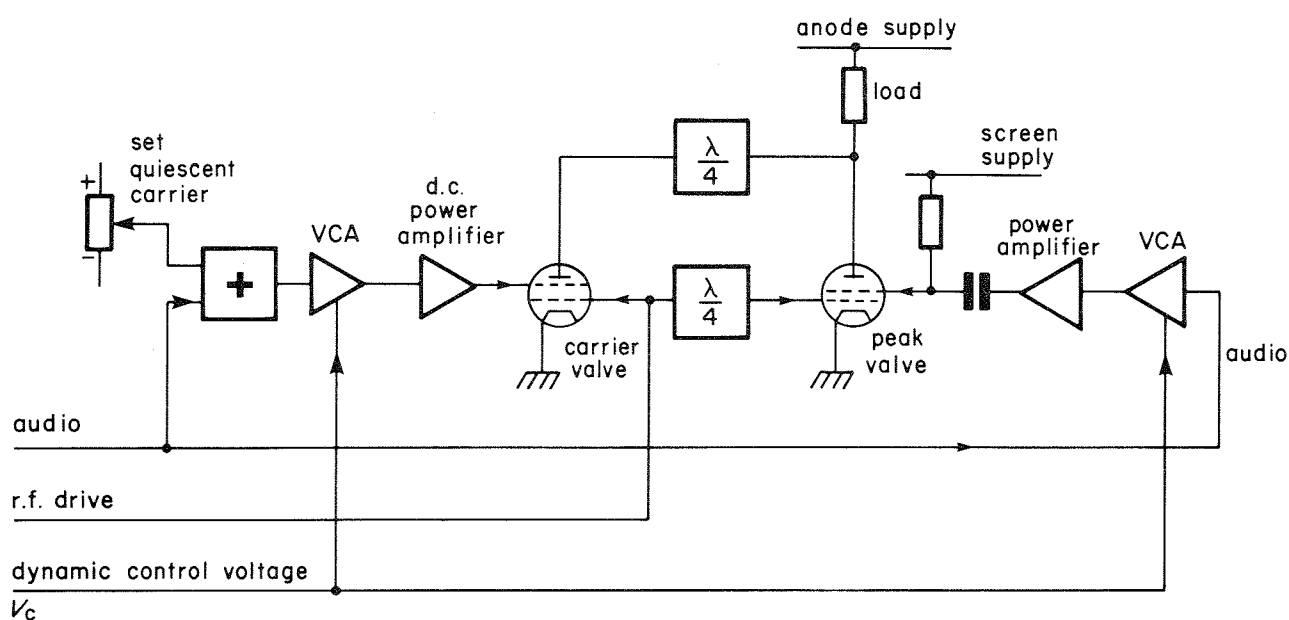
Fig. 7 — Radiation compression : embodiment for impedance-modulated amplifier.

In the receivers examined the mean time taken for the a.g.c. to restore gain to within 2 dB of the final steady state, following the abrupt reduction of applied signal level, was about 20 ms. Where the full amount of control being effected is small, this transient level discrepancy seems unlikely to be obtrusive.

A.G.C. equilibrium following an abrupt increase of signal level was, in the cases examined, substantially restored within a few tens of milliseconds. Since the transmitter compressor recovery time envisaged is of the order of 200 ms (Section 4.4.2), a.g.c. tracking during this phase of operation will be extremely close and no impairment due to mistracking is to be expected.

5. Preliminary subjective evaluation

5.1. General

The subjective assessment of an a.m. companding system is obviously influenced by reception conditions and by the receivers used by the listeners. It was therefore decided to carry out over-air tests, with listeners using their own receivers at their normal listening sites, thus to ensure that a wide range of practical listening conditions was explored.

However, though no formal subjective tests were conducted at this stage, numerous demonstrations were presented and some initial impressions regarding performance were reached informally.

5.2. Informal laboratory listening tests

The apparatus used in the laboratory at this stage was essentially that indicated in Fig. 3, giving a maximum of 6 dB compression at 100% modulation. Additionally, means were provided for introducing interfering signals at controlled relative levels, and for a ready comparison of the companding arrangement with a conventional system having the same quiescent carrier power, for reference. Means were not available at this stage for defining the signal field strength existing at the receiver.

Demonstrations were given to a considerable number of listeners, using a range of receivers, and the question was raised as to whether there were any differences of quality between the two conditions presented which could be attributed to gain-fluctuation effects in good reception conditions — i.e. to inadequately compensated compression. The consensus on such occasions

was that any such effects were minimal or non-existent, and could therefore be ignored.

The effects of programme-modulated interference were demonstrated by introducing modulated co-channel and adjacent-channel interfering signals. Under adverse, but still 'acceptable' conditions the companding system was generally considered to be not greatly worse than the conventional system, but the difference became more marked under very adverse — probably unacceptable — reception conditions.

5.3. Over-air tests

In view of the generally encouraging assessments of performance reached informally in the laboratory it was decided to carry out over-air tests to obtain an indication of system performance under a wide range of practical reception conditions, as discussed in the previous Section. The transmitters concerned were modified to produce the desired compression operation — in the first instance with 6 dB maximum compression — and alternatively to provide a source of a conventional signal on the same frequency, as a reference. The tests were each planned to occupy only a relatively short period, during late evening hours and questionnaires were distributed to those broadcasting staff who, it was hoped, would be able to listen.

The first two such over-air test sessions were almost totally unproductive. In the first case only five listeners responded, and their reactions suggested a very high level of interference — in one case, at least, the signal was quite unusable — taking the form of a near co-channel unmodulated carrier. The results, such as they were, were unfavourable for the companding system and the only conclusion drawn was that 6 dB maximum compression was probably excessive, at least under such conditions.

In view of the above conclusion the degree of dynamic compression provided for the second over-air test was of a reduced amount, about 1.75 dB maximum. However, the results of this test were largely invalidated by an anomaly in the line-up of the reference transmitter.

For the third over-air trial, two compression laws were used. These are indicated in Fig. 8 and provided a choice of either 1.1 dB or 2.7 dB maximum compression.
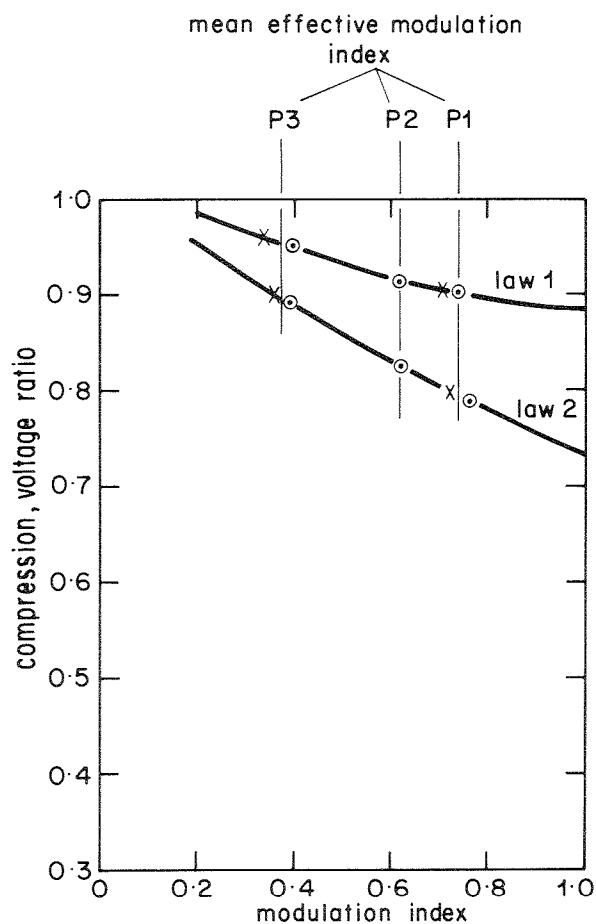
Fig. 8 — Compression laws used in third over-air tests.

⊙ Points derived from estimated power reductions

✕ Points derived from measured power reductions

This test session was carried out in a single period of about half-an-hour. In order to allow the two compression laws to be compared, whilst restricting the test to the single session, only three programme items could be included. The items chosen, piano, speech and soprano voice were selected on the basis of past experience as being among the most likely to disclose weaknesses of the technique being assessed.

On this occasion a useful response was ensured by arranging for a number of broadcasting staff to listen to the radiated tests at sites likely to yield a range of marginal reception conditions.

Each test programme item was radiated four times in an ABAB sequence, where A and B represent conventional or compressed operation (or vice versa) in an arbitrary sequence. The listeners were asked to indicate their preferences using the CCIR 7-point comparison scale given in

Table I.

This procedure was followed for the three programme items and the two compression laws being compared.

TABLE I

7 -point comparison scale	
Grade	Comparison
+3	B much better than A
+2	B better than A
+1	B slightly better than A
0	B same as (or equivalent to) A
−1	B slightly worse than A
−2	B worse than A
−3	B much worse than A

In all, 23 completed questionnaires were returned — 13 of these from listeners who commented on the presence of interference, and 10 who did not. In 17 cases it was possible to locate the listening site on a field-strength contour map of the area. Of these 17 only 6, all of whom were substantially on, or inside, the 15mV/m contour (a typical night-time service limit) did not comment on the presence of interference. Four listeners inside the 15mV/m contour, and all listeners significantly outside the contour, mentioned interference.

Table II* lists the mean gradings and (standard deviations) for the various programme items and for the two compression laws. Column (a) gives the overall results and Columns (b) and (c) give the corresponding data for those listeners who noted the presence of interference, and those who did not, respectively.

These results are generally encouraging. Using compression Law 1 the worst overall mean grading for any of the test items was −0.13 (−0.23 for those listeners commenting on the presence of interference) where −1 indicates "slightly worse

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* The results presented throughout this Report have been arranged so that a negative grade indicates a preference for conventional operation.

TABLE II

Test radiated from Radio Bristol, 24/5/84 mean grading (standard deviation):

Programme	Law	(a) Overall	(b) Interference mentioned (13 results)	(c) Interference not mentioned (10 results)
Speech	1	−0.13 (0.96)	−0.23 (0.94)	0 (1.04)
	2	−0.07 (1.05)	−0.12 (1.19)	0 (0.95)
Soprano	1	+0.04 (0.91)	0 (0.83)	+0.1 (1.11)
	2	−0.70 (1.15)	−1.00 (1.01)	−0.30 (1.26)
Piano	1	+0.17 (0.82)	−0.08 (0.87)	+0.5 (0.70)
	2	−0.13 (1.15)	−0.31 (1.12)	+0.1 (1.20)
All items	1	+0.03 (0.91)	−0.10 (1.01)	+0.2 (1.14)
	2	−0.30 (1.16)	−0.47 (1.30)	−0.07 (1.26)

than" conventional operation. With the exception of one test item (soprano), for which an overall mean grade of −0.7 was obtained (−1 for those listeners commenting on presence of interference) the results for Law 2 were of the same order. Throughout the whole test only two individual gradings of −3 were recorded. These results suggest that no general pronounced degradation of performance would result from the introduction of a.m. compression using either of the laws indicated in Fig. 8.

However, applying the condition that any degradation of service by other than a minimal amount is to be avoided − Law 2 might be considered unacceptable, particularly with performance in poor reception conditions in mind. Law 1, on the other hand − and possibly some intermediate law − would probably be acceptable.

The response to this single test session, though markedly better than that to the earlier series of tests, was still somewhat limited. Further, the test programme material used for the single session, though chosen to test the compression technique critically, was necessarily restricted in scope. For these reasons the results obtained should be treated with caution, and a further extended trial is obviously necessary.

6. Transmitter power consumption

6.1. General

Radiation compression acts directly on the transmitter output signal, and its effect on the input power demand is compounded by considerations of transmitter efficiency. However, where this efficiency can be assumed to be independent of modulation level, the reduction of output power, taken as a percentage, can be used to indicate also the reduction of input power.

The transmitter power output reduction resulting from a.m. radiation compression can readily be calculated or measured for sinusoidal modulation under static conditions. However, it is by no means as simple to derive this information for normal programme modulation where the mean compression and hence the mean power reduction factor, depends on the level statistics of the modulation programme signal. The effect of radiation compression on transmitter output power for normal audio programme signal modulation is considered in the following Sections in two ways − firstly by estimation from programme level statistics data for the programmes concerned and, secondly, by indirect measurement.

6.2. Estimation of mean output power with programme-signal modulation

In an a.m. radiation compression system the amount of compression — and therefore the output power reduction — at any instant is determined by a control voltage developed within the compressor. The effective mean output power reduction for a particular compression law, with normal programme-signal modulation, can therefore be estimated for a particular programme from a knowledge of the level statistics of the control voltage, which is related to the modulation level, and of the compression law itself.

In the apparatus used for the over-air trials the control voltage was derived by an arrangement similar in essentials to that indicated in Fig. 4. In order to estimate the output power reductions attainable a control voltage derived from the programme signals concerned by rectification and smoothing with appropriate time constants, was analysed using existing appparatus.[5] The results of these analyses were arranged so as to indicate the proportion of time for which the control voltage lay in the level intervals corresponding to $m = 0.0$ to $m = 0.1$, $m = 0.1$ to $m = 0.2$, etc., to $m = 0.9$ to $m = 1.0$.

Table III shows data in this form for programme items typical of three different services, each analysed over a period of about half an hour. Programme 1 (P1) comprised predominantly 'Pop' recordings with short linking voice-over announcements, Programme 3 (P3), on the other hand, consisted mainly of classical music and a news broadcast while Programme 2 (P2) ranged from speech and light classical music to 'Pop'. In each case the programme signals were pre-processed in the manner normal for the m.f. service concerned. The energy output in any modulation range can be estimated by the product of terms (a), (b) and (c) where,

(a) is the power output of a conventional system at that level of modulation

(b) is the proportion of time for which the level of modulation lies within the range defined* (Table III)

(c) is the appropriate power reduction factor* (Table IV)

* The single figures used in calculation to represent performance figures within the given modulation ranges are those applying at the bottom edge of the appropriate ranges.

The effective overall energy output can then be estimated by integrating the products of the (a) and (b) terms above.

TABLE III

Statistical analysis of control voltage derived from test programme tapes: proportion of time within given modulation index ranges

Modulation Index	Programme		
Range	P1	P2	P3
0.9 − 1.0	0.28	0.12	0.05
0.8 − 0.9	0.31	0.18	0.05
0.7 − 0.8	0.21	0.22	0.08
0.6 − 0.7	0.11	0.18	0.10
0.5 − 0.6	0.05	0.11	0.11
0.4 − 0.5	0.02	0.07	0.13
0.3 − 0.4	0.008	0.05	0.16
0.2 − 0.3	0.006	0.033	0.13
0.1 − 0.2	0.005	0.027	0.10
0 − 0.1	0.001	0.01	0.09

Table IV shows for the two compression laws of Figure 8 the power reduction applicable for sinusoidal modulating signals at modulation index values $m = 0, 0.1, 0.2$ etc., to $m = 1$.

TABLE IV

Normalised transmitter output power at various levels of sinusoidal modulation, relative to conventional system

Modulation index	Power reduction factor	
M	Law 1	Law 2
1.0	0.781	0.537
0.9	0.790	0.567
0.8	0.805	0.604
0.7	0.823	0.645
0.6	0.848	0.689
0.5	0.874	0.740
0.4	0.903	0.792
0.3	0.931	0.848
0.2	0.964	0.912
0.1	1.0	0.978
0	1.0	1.0

Table V lists the output power reductions for the two compression laws of Fig. 8 for the

types of programme material described previously, calculated in this way. The estimated economies range from 9.7% for P3 programme material using compression Law 1, to 37.6% for P1 programme using Law 2.

TABLE V

Estimated mean output power reduction relative to conventional operation

Programme	Compression	
	Law 1	Law 2
P1	18.4%	37.6%
P2	15.6%	32.1%
P3	9.7%	20.7%

6.3. Measurement of mean output power

It was noted earlier that the task of measuring transmitter output power directly under normal programme modulation conditions is not simple. It requires, in effect, the r.f. equivalent of a domestic kW-hour meter.

In the present investigation this measurement was made indirectly. A portion of the transmitter output was multiplied by a stable signal displaced 10 kHz from the transmitter carrier frequency, and the resulting products were low-pass filtered to isolate the 10 kHz ± f_{mod} components. This 'frequency-shifted' version of the transmitter output was then analysed to compare the mean effective transmitter output powers under different conditions, using audio-signal power-integration apparatus originally devised for measurements on baseband sound-programme signals.

In practice, selected recorded programme material (the material also used for the estimation described in Section 6.2) was used to modulate the transmitter (a) operated conventionally and (b) with the compression laws of Fig. 8 in operation, in turn. The frequency-shifted transmitter output was then recorded for subsequent analysis, using a digital audio recorder to achieve the stability necessary to preserve accurately the relatively small differences being investigated.

The results of the measurements on the two types of programme, P3 and P1, and for the two compression laws of Fig. 8 are given in Table VI. The measured output power reductions range from 7.9% for P3 programme, using compression Law 1, to 36.1% for P1 programme using compression Law 2, and, in general, are in very good agreement with the estimated figures given earlier in Table V.

TABLE VI

Measured mean output power reduction relative to conventional operation

Programme	Compression	
	Law 1	Law 2
P1	17.4%	36.1%
P3	7.9%	19.2%

Points corresponding to the percentage power savings estimated and measured as described above have been plotted on the curves for Law 1 and Law 2 in Fig. 8, and from these it is possible to estimate the mean effective modulation indices appropriate in the present context for the services concerned. The values, deduced in this way, are approximately m = 0.37, m = 0.62 and m = 0.74 for P3, P2 and P1 respectively.

7. Formal laboratory subjective tests

7.1. General

It was at this stage decided to carry out a formal laboratory subjective assessment of the a.m. companding technique, with particular emphasis on a comparison of its power saving potential with that of a conventional system having its output power so reduced (statically) as to yield the same overall subjective effect.

New laboratory apparatus was therefore constructed to give the flexibility of operation required for the investigation.

7.2. Laboratory apparatus

The new laboratory apparatus constructed for this investigation was essentially as indicated in Fig. 4, with the 'Compression' control fitted on the front panel and arranged to provide the range of compression laws indicated in Fig. 9. Provision was made for the dynamic control to be
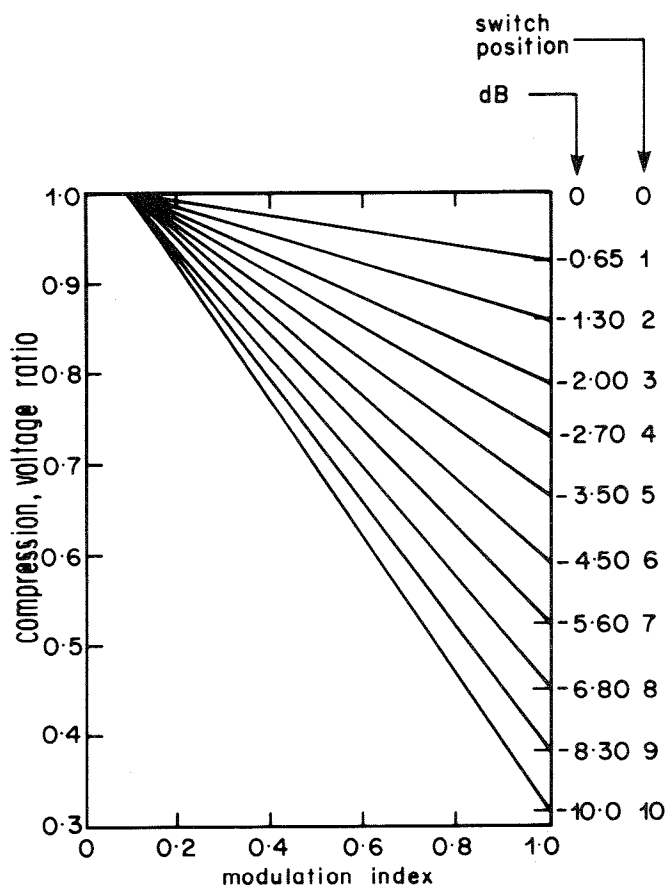
Fig. 9 — Range of dynamic compression laws provided for laboratory subjective tests.

Fig. 10 — Range of static attenuation values provided for laboratory subjective tests.

disabled by remote control, and for any of an appropriate range of fixed potentials, also selected by a front panel control, to be applied to the second modulator to set the apparatus output in this conventional mode to any of the levels indicated in Fig. 10. These levels in fact correspond to the compression levels at 100% modulation in the dynamic mode.

Arrangements were also made to introduce an interfering carrier, either modulated or un-modulated, at an adjustable relative level, and to set the level of the composite signal as desired.

For convenience the various dynamic compression laws of Fig. 9 will be identified as DO, D1 . . . . D10, corresponding to the associated switch positions, and the corresponding range of reduced power conditions in the conventional mode, Fig. 10, as Co, C1 . . . . C10. The "D" and the "C" values are substantially linearly-spaced in terms of voltage compression ratio, but the data obtained in the subjective analysis were translated individually into equivalent decibel values of attenuation before analysis.
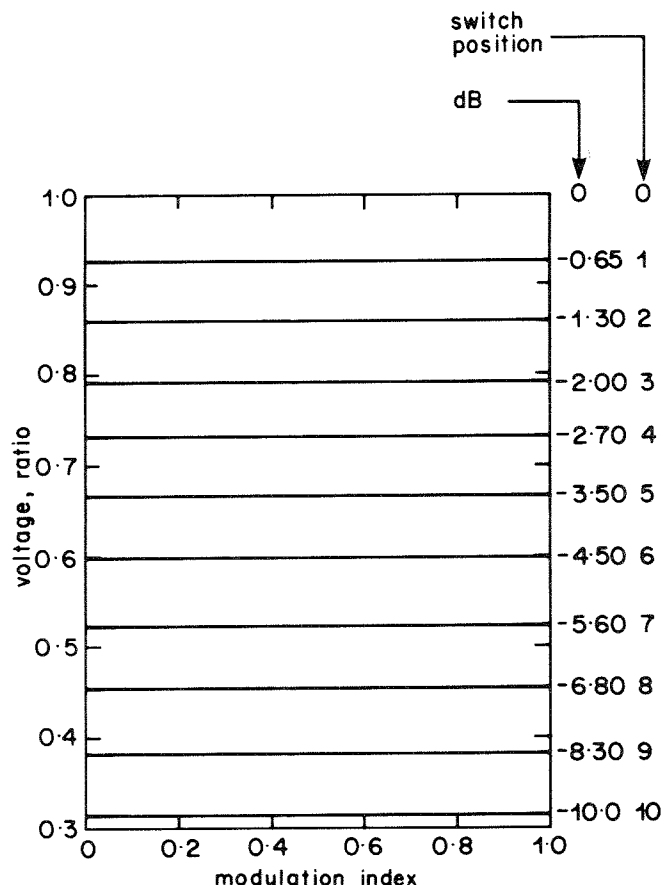
A double-layer mesh cage was used to house the radio receivers being used (in turn) for the tests. The outer, earthed, layer provided screening to prevent extraneous interference from broadcast transmissions; the inner layer, split lengthwise to form effectively a long, single-turn, coil was driven by the desired test signal, and provided a substantially uniform field in the inner space housing the receiver.

The time constants adopted initially for the dynamic mode were those mentioned previously in Section 4.4.2. However, during preliminary listening on a particularly stringent soprano voice test passage, an objectionable distortion was noted by some critical listeners. It was found that this was attributable to the combination of the short attack period and rapid recovery: the effect was overcome by increasing the attack time constant to about 5 ms*.

* A corresponding programme time-delay circuit, necessary for non-overshoot operations, could be achieved with a standard of performance appropriate for the present application by the use of a 'bucket-brigade' delay-line integrated circuit.

In all cases wanted and interfering audio modulating signals were band restricted to 5.2 kHz to represent normal operating conditions.

7.3. Subjective test conditions

To reduce the effort required in the subjective investigation to manageable proportions tests were carried out under only three different reception conditions:—

(a) in a 15 mV/m field strength, without added interference

(b) in a 15 mV/m field strength, with a locked co-channel interfering carrier at a protection ratio of 26 dB, fully modulated by a 'Pop' music programme signal, processed for m.f. transmission

(c) in a 2mV/m field strength without added interference.

15mV/m and 2mV/m field strengths were chosen to represent typical service limits for night-time and day-time reception respectively. The 26 dB protection ratio represents the least-favourable limit for co-channel interference proposed for service planning purposes in CCIR Report 794 (1978)**.

The restriction of the form of interference to locked co-channel only was imposed arbitrarily for economy of effort. However, to make the tests as stringent as possible a carrier phasing close to 180°, the least favourable condition, was adopted.

Listeners carried out the test individually. Each was asked to bring from his home, if possible, and use for the tests, the receiver on which he would normally listen to m.f., a.m. radio. Before he started the test session he was asked to tune the receiver and to adjust the volume and any tone controls as he would do at home and to make any subsequent adjustment he considered necessary at any time during the test.

Three test programme items were initially chosen as likely to constitute stringent test material, speech, soprano singing and piano, these being processed for an m.f., a.m. service carrying predominantly classical music. In the light of the results obtained for these items tests were carried out subsequently on a further speech

** This figure was proposed by Japan: a less stringent standard (30 dB) was proposed by the EBU.

item which was processed for a service carrying a range of programme types, to represent the more critical contents of such a service.

A total of 12 listeners, most of them having experience in assessing the quality of sound programmes, took part in the tests.

7.4. Subjective test procedure

At the beginning of each test session each listener was advised that programme quality degradation might at times be present.

His attention was drawn, for example, to the possibility of impairment due to noise or interference effects — either steady in level or programme modulated — and to possible disturbance of the relative levels within a programme signal. He was asked to take all forms of impairment into account, and to base his assessments on the overall effects. He was not informed of the test details or of the significance or the effect of the controls which he was required to operate during tests. But he was being asked, in effect, to make the comparison gradings and apparatus adjustments described below (not necessarily in the order given) for each test programme item.

1. With the receiver in a 15 mV/m field strength and without interference

   (a) Grade an assessment of the dynamic compression system, with Law "D"10 in operation, relative to that for a conventional system with no output reduction, i.e. "C"0 (identical quiescent carrier levels), using the 7-point CCIR comparison scale shown in Table I. Note grade.

   (b) If "D"10 is graded as inferior to "C"0, adjust the "D" control (to reduce the amount of dynamic compression) until the "D" condition is "just perceptibly" worse than the "C" condition. Note position of "D" control.

2. With the receiver in a 15 mV/m field strength and with 'Pop' music modulated co-channel interfering signal at a protection ratio of 26 dB.

   (a) as 1 (a)

   (b) as 1 (b)

(c) Leaving the "D" control as set in 2(b) adjust the "C" control (to reduce the steady output level of the conventional system) until the "C" condition is now "just perceptibly" worse than the "D" condition. Note setting of the "C" control.

3. As 2, but in a 2 mV/m field strength and without interference.

These tests were carried out for the various test items noted above.

7.5. Test results

The mean scores and standard deviations for the various tests are listed in Table VII under the test condition categories given in Section 7.4.

In the present context, however, a system performance corresponding to a mean grading figure would not be acceptable in practice since it implies that about half those listening would have given a worse grading, albeit only under adverse reception conditions and on critical programme items. A second listing of results is therefore given in Table VIII, showing system performance parameters corresponding to a 90% satisfaction* under the conditions of the test. This latter analysis was based on an assumption of a Normal Distribution of results, and it is encouraging to note that, of all the individual results analysed, a total of 11% actually fell outside the 90% satisfaction groups for the performance standards thus defined — a figure very close to the theoretical value of 10%.

In some of the (b) test conditions one or more listeners found no fault with the "D"10 condition (i.e Grade 0), implying that a range of dynamic control greater than the 10 dB provided might also have been acceptable to them. Their "D" control setting for the corresponding (b) test has however been taken as "D"10 for analysis and cases where this occurred have been indicated in Table VII by a 'greater than' sign preceding the mean figure in the (b) row concerned.

* The instructions to listeners to set equipment controls to obtain "just perceptibly worse" conditions implies marginally less than 90% of listeners being unaware of any degradation. However, in practical conditions, where the reference condition is not available for comparison, more than 90% would be expected to be unaware of any degradation.

It is of interest to compare the results in Table VII with those obtained from the earlier over-air tests described in Section 5.3 and presented in Table II. These suggested that Law 2, corresponding to a compression of 2.7 dB at 100% modulation, might be considered unacceptable. However, this conclusion was largely determined by the adverse result for the 'soprano' programme item and is attributed to the distortion due to too short an attack time in the dynamic control system. As mentioned in Section 7.2 this attack time was increased to 5 ms for the formal laboratory tests in order to avoid this problem. As can be seen in Tables VII and VIII this was an effective measure as the "D" settings for the soprano item are more or less in line with those for the other items.

7.6. Interpretation of test results

The most obvious point of note in Table VII is the negligibly small adverse grading of the dynamic controlled system under good reception conditions, even with the 10 dB maximum compression law in use. This result is due to a perhaps surprisingly effective expanding action in the majority of receivers, and indicates that disturbance of programme dynamics is most unlikely to be a significant source of degradation in good reception conditions, particularly at the lower degrees of compression more likely to be adopted in practice.

The negative assessment gradings of the dynamic system under adverse reception conditions, up to −2.04, reflect the effects of programme-modulated noise and interference, and possibly of inadequate expander action in some of the low signal-level tests. However such results are not unexpected at the maximum degree of compression provided, and the following analysis is directed towards examining operating parameters giving impairment imperceptible to 90% of the listeners under the condition of the test.

The performance parameters listed in Table VIII, rows 2(b) and 3(b), are those estimated for dynamic control to give impairment "just perceptibly worse" than that of the reference conventional system under the conditions of the tests, while the figures given in rows 2(c) and 3(c) indicate amounts of static power reduction giving performance standards just perceptibly worse than those defined in 2(b) and 3(b) for dynamic control. We thus have determined two conditions of static operation, one at full level and one at reduced level, giving respectively standards of performance "just perceptibly better" and "just perceptibly worse" than that of the dynamic system at the degrees of compression just defined.

TABLE VII

Subjective assessments : control settings corresponding to impairments imperceptible to 50% of listeners

Test	Grading/control setting (Standard Deviation)			
	Soprano (P3)	Piano (P3)	Speech (P3)	Speech (P2)
15mV/m, no interference → 1 (a) Rel. Grading (b) "D" setting, dB	−0.17 (0.33) > 9.28 (1.76)	+0.04 (0.66) >9.83 (0.92)	−0.29 (0.58) >9.13 (1.77)	−0.04 (0.14) >10.0
15mV/m, with R1 modulated co-channel interference → 2 (a) Rel. Grading (b) "D" setting, dB (c) "C" setting, dB	−0.42 (0.63) >9.08 (1.52) 3.98 (1.51)	−0.92 (0.56) >7.45 (1.81) 4.48 (1.59)	−0.25 (0.40) >9.37 (1.50) 3.81 (1.47)	−0.58 (0.47) >9.43 (1.64) 4.24 (1.64)
2mV/m, no interference → 3 (a) Rel. Grading (b) "D" setting, dB (c) "C" setting, dB	−1.02 (1.00) >7.54 (2.9) 3.14 (0.74)	−2.14 (0.67) 5.20 (2.17) 3.47 (0.70)	−1.36 (0.95) >6.13 (3.08) 2.92 (1.26)	−2.04 (0.69) 4.80 (0.91) 3.23 (0.98)

TABLE VIII

Subjective assessments : control settings corresponding to impairments imperceptible to 90% of listeners

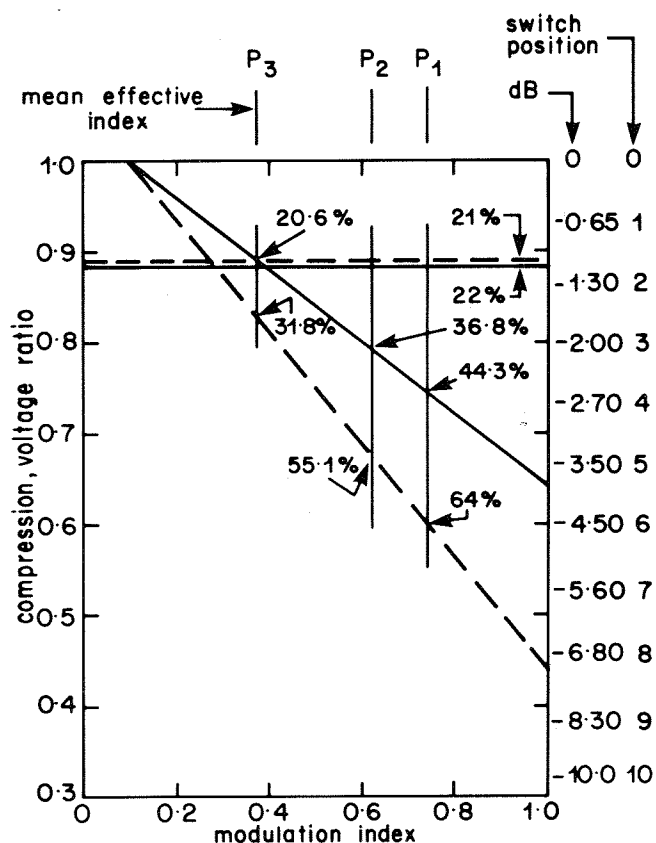| Test	Soprano (P3)	Piano (P3)	Speech (P3)	Speech (P2)
15mV/m, with R1 modulated co-channel interference → 2 (b) "D" setting, dB (c) "C" setting, dB	7.13 2.05	5.13 2.44	7.45 1.93	8.35 2.14
2mV/m, no interference → 3 (b) "D" setting, dB (c) "C" setting, dB	3.83 2.19	2.42 2.57	2.19 1.31	3.64 1.98

Fig. 11 — Subjectively equivalent dynamic and static power reduction characteristics : impairment imperceptible to 90% of listeners on direct comparison with conventional operation.

Soprano voice, P3

———————— 2mV/m No interference
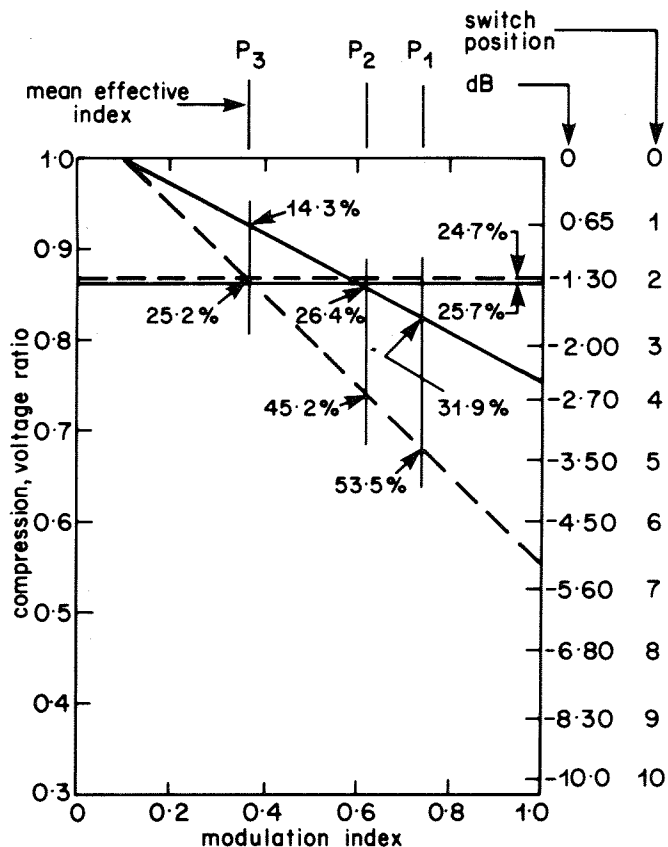
— — — — 15mV/m R1 interference

Fig. 12 — Subjectively equivalent dynamic and static power reduction characteristics: impairment imperceptible to 90% of listeners on direct comparison with conventional operation.

Piano, P3

———————— 2mV/m No interference

— — — — 15mV/m R1 interference

The mean of these two values of output in static operation thus is a good indication of the static power which is equivalent subjectively to dynamic control giving impairment imperceptible to 90% of listeners in the particular test concerned.

Figs. 11 to 14 indicate the pairs of static and dynamic operating conditions, deduced by the process described above as being subjectively equivalent for the various test items, and for the two forms of adverse reception conditions considered. In order to indicate the power-saving potentials these figures also give the estimated mean effective modulation indices for the three programme types used (P1—largely 'Pop' music; P2—mixed, including some light classical music and 'Pop' and P3—mainly speech and classical music), derived by the process described in Section 6.3.

For the three P3 programme types, i.e. Soprano Voice, Piano and P3 Speech (Figs. 11 to 13), the indicated power savings were, in three cases almost equal at the P3 mean modulation index level for the subjectively equivalent static and dynamic operating conditions — in one case the static condition indicated the greater potential for power saving and in two cases dynamic operation indicated the greater potential. The indications are, therefore, that at the P3 mean modulation level, the static and dynamic power-reduction techniques, if arranged to give equivalent subjective performance, will also have a similar potential for power saving.

However it is of interest also to consider radio services providing a range of programme types. The processing parameters will in this case be set by the most critical programme type which may be, for example, speech of the P3 type.
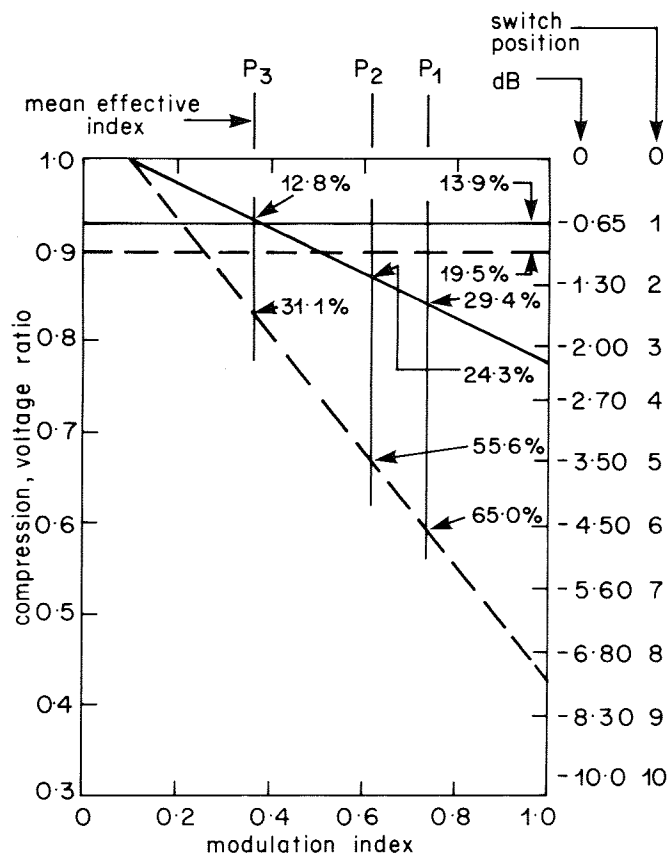
Fig. 13 — Subjectively equivalent dynamic and static power reduction characteristics: impairment imperceptible to 90% of listeners on direct comparison with conventional operation.

Speech, P3

——————— 2mV/m   No interference

— — — — 15mV/m   R1 interference

Fig. 13 indicates that static and dynamic control have similar power-saving potential at the P3 modulation level in these circumstances. But if now the programme material also includes extended periods of high modulation such as to raise the mean effective modulation index, the power-saving potential of the dynamic arrangement will show a significant advantage over that of the static arrangement. In Fig. 13 (P3 speech) the static power-saving potential indicated for the 10%/90% threshold condition is about 14% over the full modulation range, while that for dynamic control is about 13% at the P3 mean modulation level, but rises to about 24% and 29% for programme material with mean effective modulation indices corresponding to those of P2 and P1 respectively.

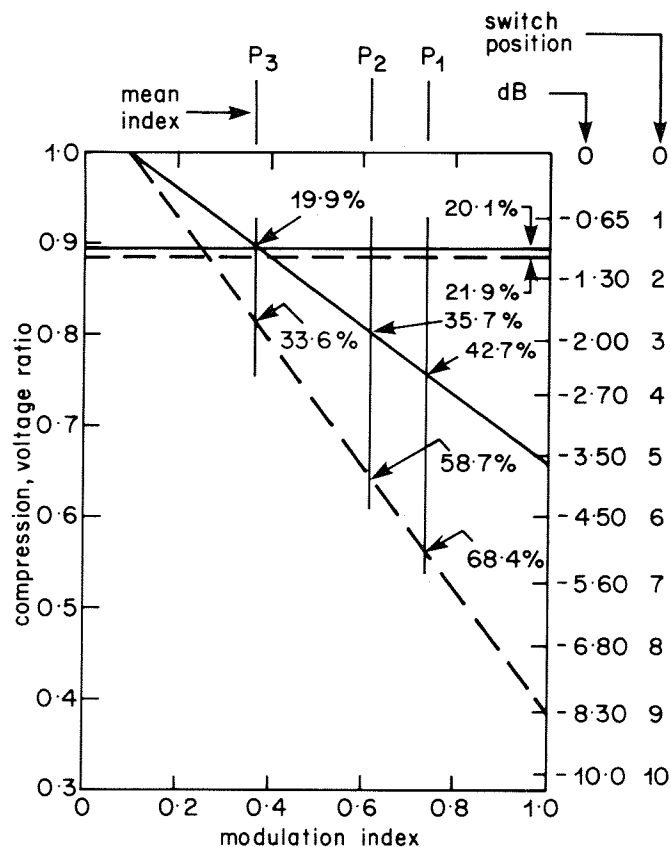The results for subjective tests using P2 speech — carried out subsequent to those for

Fig. 14 — Subjectively equivalent dynamic and static power reduction characteristics: impairment imperceptible to 90% of listeners on direct comparison with conventional operation.

Speech, P2

——————— 2mV/m   No interference

— — — 15mV/m   R1 interference

P3 items in view of the above considerations — are given in Fig. 14. The results are similar qualitatively to those for P3 type speech in that the power savings indicated at the P3 mean modulation level are very similar for static and dynamic control. Dynamic control becomes progressively more advantageous for programmes with higher mean modulation levels.

However the P2 type speech used was evidently less critical than the P3 speech passage since the results indicate a tolerance to greater amounts of control, either dynamic or static. The saving potential indicated at the P3 mean modulation level is about 20% for both static and dynamic control, while at the P2 and P1 level potential savings of about 36% and 43% respectively are indicated.

The figures discussed above all relate to

dynamic controlled systems in which the carrier level is allowed to return to the same value as that of the reference conventional system under low-modulation and quiescent conditions. Further, they relate to a 10% "just perceptible impairment" performance in the conditions of the tests, which included facilities for switching directly between the two conditions being compared. When, as in practice, no such direct comparison can be made, the percentage of listeners noting any degradation with the parameters defined would be expected to be markedly reduced. If even this standard is considered inadequate an improved subjective performance could be attained either by adopting an enhanced quiescent carrier level (international regulations permitting) for the dynamic arrangement, or by simply reducing the degree of compression applied. Both these approaches would, of course, reduce the power saving, but the former arrangement would give a potential quality improvement, particularly during periods of low modulation.

8. Transmitter operating costs

The estimates of power saving given in the previous Sections relate to changes of transmitter mean output power. If, however, we assume transmitter efficiency to be independent of modulation level and of any other factor, the figures given can be applied directly, as percentages, to obtain estimates of the effects on transmitter input power values.

Actual cost savings will, of course, depend on the number of transmitters involved, on the mean effective level of modulation, on the compression law applied, on the utilisation factors of the transmitters concerned and on the cost of the energy being used. However, by way of illustration, consider a service provided by, say, twenty transmitters each of 100 kW output-power rating and 60% efficiency, operating on a 24 out of 24 hour utilisation factor on energy supplied at, say, £0.035 per kWh. In such a case the energy consumed would be about 29000 MWh annually at a cost of about £1,000,000. A power reduction of, say, 10% would in these circumstances lead to a saving of £100,000.

9. Conclusions

This Report has described a radio-frequency companding technique which can be applied to amplitude-modulated transmission, using the a.g.c. action provided in virtually all modern receivers to compensate for the compression of the radiated signal imposed deliberately at the transmitter.

The technique is not new, but its implementation can be more readily achieved, using modern developments in technology, than was possible when it was first conceived.

Subjective tests have been carried out and measurements made in order to estimate its likely effects on programme quality and, further, of its potential for power saving using compression laws likely to introduce only minimal quality degradation even under adverse reception conditions.

The subjective assessments indicate, firstly, that no general significant quality degradation of received programme is likely to be noticed in good reception conditions, even using amounts of compression considerably greater than any likely to be considered for practical application.

The subjective assessments also enabled performance parameters to be estimated, for both dynamic compression and for static power reduction, such as would give impairment judged to be imperceptible to 90% of listeners in the very stringent conditions of the tests. These results indicate that the two forms of control, static and dynamic, have similar power saving potential for equivalent subjective effect when applied to a service containing critical programme material (for example, high-quality speech) and of generally low modulation level.

However, the results further suggest that, where the programme contains critical items, which determine the acceptable amount of static or dynamic control, but includes also other material, such as 'Pop' music, which results in a high mean modulation level, the power saving potential of a dynamic system can be appreciably greater than that of a static power reduction arrangement giving an equivalent subjective effect on the critical programme passages.

The results of the investigation are thus encouraging. However it is acknowledged that the subjective tests which have been carried out have necessarily been restricted in the range of reception conditions explored, the types of test items used, and the types of receiver and number of listeners taking part in the study. Further, practical technical considerations have so far precluded direct power measurements on a representative transmitter over an extended period.

It is therefore concluded that although the results described in this Report do not justify an extensive introduction of an a.m. companding

arrangement in service at this stage, they are of sufficient interest and attraction to merit the consideration of an extended field trial using a representative high-power transmitter in service operation so as to assess the system potential fully under practical conditions.

This investigation has been restricted to the modulation characteristics and reception conditions appropriate to the domestic medium-frequency Radio broadcasting services of the BBC. However, it might well be that the radio-frequency companding technique could also be advantageous in the high-frequency transmissions of the External services of the BBC. Indeed the power-saving potential may then be greater as the degree of programme compression tends to be higher and also the transmitter power is higher in h.f. services. Alternatively, the important aspect of 'audibility' in External Broadcasting may be improved by enhancing the unmodulated carrier level, albeit with a reduction in power saving. However, in view of the different reception conditions, i.e. severely fading signals possibly subject to high levels of interference, further investigations would be necessary to establish what benefits could be derived.

10. Acknowledgements

11. References

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